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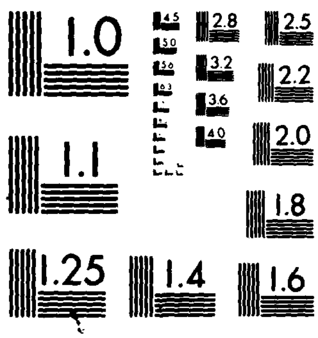

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Phase Report
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INVESTIGATION OF LOW LEVEL AIRCRAFT NONAVIONIC NONLINEAR INTERFERENCE

University of South Florida

Dr. J. L. Allen

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APPROVED:

GARY L. BROCK, Captain, USAF
Project Engineer

APPROVED: Quentin J. Porter

QUENTIN J. PORTER
Acting Chief, Reliability & Compatibility Division

FOR THE COMMANDER: John P. Huss

JOHN P. HUSS
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High transmitter power levels combined with increased receiver sensitivity in multi-channel communication systems have led to operational problems caused by passively generated intermodulation products (IM). This report summarizes the results of a literature survey on causes, effects and reduction techniques for passively generated IM interference. An extensive list of references is included.

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I. INTRODUCTION

Advances in technology have led to communication systems with higher transmitter power and increased receiver sensitivity simultaneous with increased use of multiple closely spaced channels and greater physical density of components. As a result, formerly unimportant nonlinear characteristics have begun to cause problems in high performance systems. Intermodulation products generated within the system or reradiated from nearby support structures or antennas find their way into highly sensitive receivers. Receiver filtering can eliminate only those extraneous signals which fall outside the intended operating band.

Existing information on passive intermodulation generation is scattered, and understanding of the basic problem is limited. The purpose of this report is to summarize findings of a literature search on passive intermodulation generation and related topics.

II. BACKGROUND

Absolute linearity exists only as a mathematical idealization. In an ideal linear system, signals would be faithfully transferred without distortion. In the real world nothing is absolutely linear, but so-called "linear" systems provide good models of many phenomena over restricted ranges of variables with specified nonlinearity tolerances. A familiar linear relationship is Ohm's law ($V = IR$) which merely defines an ideal linear resistance. In fact, there is no real resistor with absolutely linear resistance. However, within the range of commonly used current densities, the resistance nonlinearity of many conductors is so minute that its effects are beyond the sensitivity of most test instruments. For most practical applications, such resistances are considered linear and the conductors are said to be "ohmic." When pushed too far or examined too closely, it is inevitable that any supposedly linear system will exhibit nonlinear effects. Such weak nonlinear effects may limit the useful signal levels in a system and thus become an important design consideration.

Many fundamental relationships in Physics have linear models as first approximations. Hooke's law on elastic properties of solids, Newton's second law of motion, and Ohm's law for electric conductors are three prominent examples. As is well known, over the elastic limit Hooke's law fails and the material under test will suffer permanent deformation. Relativistic effects are introduced into the laws of motion as linearity fails in Newton's second law. In electromagnetic theory, Maxwell's equations are linear but the constituent equations which describe the electromagnetic macroscopic properties of matter may be nonlinear. Ohm's law in the form $J = \sigma E$ (σ = conductivity, J = current density, E = electric field intensity) is the constituent equation for conductors. Nonlinear materials may generate harmonics and intermodulation products in an intended (mixers, limiters) or unintended fashion in a communication system. In the latter case the spurious frequency components are called harmonic and intermodulation interference.

The generation of harmonic and intermodulation (IM) interference by weakly nonlinear mechanisms in normally passive structural parts and signal path components can lead to severe degradation of performance in multi-carrier communication systems. Such systems are frequently associated with satellite, deep space probe, aircraft, ground mobile, and shipborne installations. Any system requiring simultaneous operation of "co-located" transmitters and receivers is susceptible. Significant problems with passively generated IM interference have been reported for several systems [A1, A7-A14]. Most reported difficulties have been for HF and UHF systems in satellite and shipborne installations. Increasingly sensitive receivers and more powerful co-located transmitters coupled with techniques such as frequency hopping almost guarantee that passively generated IM's will play an increasingly important role in system design, manufacturing techniques and maintenance.

In general, all generated IM components with frequencies that fall within local receiver bands must be minimized. The IM interference problem can be particularly severe in co-located systems on relatively small, isolated platforms. For a modern communication satellite, it is generally required that high-power multi-channel transmitters and super-sensitive broadband receivers be packed in a limited space. Power level difference between transmit and receive signals can exceed 200 dB. Transmitters and receivers are often coupled to a common antenna through a diplexer to save space and weight. Weak, parasitic, nonlinearities in the diplexer, antenna or other common elements will mix the signals generating spurious intermodulation products when two or more transmitting channels are used simultaneously. Even-order IM products seldom cause interference problems in a moderate or narrow bandwidth system. Odd-order IMs may fall in the receive frequency band. When these IMs reach the level of the receiver noise power, receiver sensitivity is degraded.

For a synchronous orbit satellite, the space attenuation alone is about 175 dB for the UHF uplink or downlink signals. If as cited in reference [B1] the interference is required to about 15 dB below the signal level, then any IM generation must be about 190 dB below the local transmitter power level. In a deep space network the ground transmitter power level may be hundreds of kilowatts with receiver sensitivities as low as -180 dBm using traveling wave masers. This means the received signal level may be approximately 250 dB below the local transmitter level with correspondingly severe requirements on levels of IMs generated. Two specific instances in which problems were encountered were (a) the development of Lincoln Experimental Satellites 5 and 6 (launched in 1967 and 1968, respectively) which had moderate IM problems of the 5th and 19th order [A9] and (b) the development of FLTSATCOM (launched in 1978) which had problems with 3rd and 5th order IMs [A-10].

Aircraft communication receivers frequently have sensitivities of approximately -90 dBm. A local transmitter power level of 100 watts and a requirement cited in reference [B1] that IM products be 15 dB below signal level would require IM levels about 155 dB below transmitter power level.

The required low levels of IM power indicates that nonlinear mechanisms in normally passive parts and vehicular structure can be very significant and may in fact be the primary limiting factor in system performance. Interfering IM signals from normally passive sources may be generated in the normal signal path (e.g., in cables, connectors, antennas, diplexers, etc.) or may alternatively be generated in some external structure and reradiated or coupled in some other manner into the signal path. Common sources of reradiated IM products include iron and steel vehicular structural parts and vibrating metal-metal contacts of all types. It should be noted that in the literature when sensitivities are specified the associated bandwidth is almost never provided.

III. IM GENERATION

A co-located system simultaneously transmitting and receiving on a number of frequencies in, say, the HF, VHF or UHF bands leads to problems concerning spectrum utilization arising from intermodulation interference produced by the high-level transmissions mixing in a nonlinear environment. Apart from nonlinear effects in the structural features of the installation, there will also be intermods generated via nonlinearities in the transmitter power amplifiers, output couplers, receiver front end, and antenna. At VHF and higher frequencies dissimilar metal interfaces may be an important contributor in connectors and cables. At lower frequencies these latter effects can usually be ignored since the naturally occurring thermal noise level is in excess of kTB watts* and would mask the spurious generation from cables and connectors.

A nonlinear transfer characteristic without memory (i.e., the output is an instantaneous function of the input voltage) can be described by a polynomial expansion

$$V_{out} = k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 + \cdots + k_N V^N \tag{1}$$

where k_1, k_2,$\cdots$, k_N are constants. When the nonlinearity is subjected to "r" unmodulated sinusoidal carriers f_1, f_2, $\cdots$, f_r, an intermodulation product f_x is given by

$$f_x = mf_1 + nf_2 + \cdots + yf_r \tag{2}$$

where m, n, $\cdots$, y are positive or negative integers and $|m| + |n| + \cdots + |y|$ denotes the order of the intermod. For the case of two excitation frequencies, V_{out} will contain various IMs with frequencies given by

---

*k is Boltzman's constant, T is temperature, B is bandwidth

$$f_{IM_{m,n}} = |mf_1 \pm nf_2| \tag{3}$$

where m and n are integers. The number $|m| + |n|$ designates the order of the IM. Fifth order IMs would be generated at frequencies $(2f_1 \pm 3f_2)$, $(4f_1 \pm f_2)$, etc.

The amplitude relationship between IM and the fundamental signals is much more complicated. The nonlinear characteristic of each system component must be characterized quantitatively. Each nonlinear contribution must be properly located in the network and combined with proper phase at the IM output port. The probability of constructive interference is greater than that of destructive interference. For two signals, assuming a random phase relation and equal amplitudes, the probability of constructive interference is 2 to 1 over destructive interference.

The number of IMs increases rapidly with the number of transmissions. The congestive effect on the receiver frequency spectrum is vividly shown in Figure 1 for 2- and 3-frequency transmissions. No attempt has been made in this figure to indicate the relative amplitudes of the components. Intermods higher than 40^{th} order have been reported as above the noise level in HF systems. Decrease in amplitude with increase in IM order is not necessarily rapid. Measurements in HF systems [A1] indicated that orders as high as the 11^{th} may be only 20 dB below the 3rd-order components. It is therefore usually not possible to identify in advance the intermods that would cause serious interference to the desired signals. Lower order IMs, such as the third and fifth, are frequently larger than the desired signals, and therefore the frequencies at which they occur are usually excluded from the frequency-assignment plan. The number of unusable frequencies becomes very large when three or more simultaneous transmissions are required particularly in a frequency-agile system. The generalized approach must therefore be to reduce or ideally eliminate the significant sources of

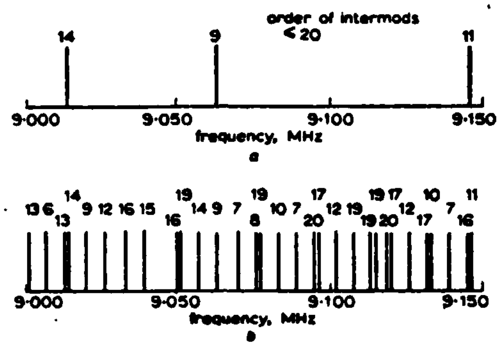

Figure 1.

Typical section of the intermodulation spectrum for 2- and 3-frequency continuous-wave transmissions

a *Two transmitters: f_1 = 1·007 MHz, f_2 = 1·882 MHz*
b *Three transmitters: f_1 = 1·007 MHz, f_2 = 1·882 MHz, f_3 = 1·347 MHz*

(After Betts [A1])

intermodulation generation to prevent the IM problem from becoming the overriding factor in limiting system characteristics.

IV. GENERATION OF IM's BY NORMALLY PASSIVE DEVICES

The unwanted, weak, nonlinearities in a supposedly "linear" passive system are difficult to pin down. From experience [A1, A7-A14] the following items have been identified as dominant contributors to nonlinearities in passive "linear" systems.

A. Connections

1. Coaxial connectors, waveguide flanges and transitions from one transmission medium to another (e.g., a coaxial to microstrip transition)
2. Metal-to-metal pressure contacts, screw covers, spring-finger contacts, press-fit contacts, point contacts, tuning screws, intermittent contacts in stranded or braided cables
3. Corrosion caused by solder flux

B. Surface finishes and materials

1. Sharp rough surfaces, burrs, cracks, scratches
2. Imbedded chips, filings, filament conductors, flaking metallic paint
3. Water vapor, solder flux contamination
4. Magnetic materials (ferrites, steel, nickel, etc.)

Physically, all of the sources of nonlinear effects listed above seem to be traceable to a few general causes.

1. Metal-to-Metal joint pressure contact variations
2. Unintentional diode junction effects
3. Plasma effects (local high field causing corona)
4. Local high current density causing resistive nonlinearity
5. Magnetic nonlinear effects

In general, nonlinearity suppression calls for precision manufacturing, tight assembly control, extreme care to ensure tight, clean joints and smooth, clean surfaces, plus avoidance of magnetic materials wherever possible. Designs should be such that the magnitudes of current densities and voltage gradients are minimized. The folloiwng paragraphs describe the most important of these nonlinearities in more detail.

1. Metal-Metal Joints [B1-B22] and [C1-C9]: Similar or dissimilar metal joints with narrow gaps can be significant sources of IM interference. This type of source arises from nonlinear conduction across the metal-metal pressure contact interface. Contact occurs at "high points" with gaps in between. Gaps are very narrow, often only about 100 Å. Under some conditions high field emission can occur in the gap areas. Vibration, temperature changes, and humidity can cause large variations in the levels of IM interference generated. Joint pressure is a key factor. IM levels reported are only 40 to 100 dB below local transmitter power levels.

Such nonlinear metal-metal joints may occur both in signal path components (e.g., connectors, braided cables, and press-fit parts) and structural parts of the installation (e.g., metallic bolted structures, antenna guywire supports, and access panels). Intermodulation products and/or harmonics are often generated at a given location and radiated to cause a problem at some nearby location.

In one laboratory study [C3] contact materials of commerical copper, commercial hard brass, commercial mild steel, aluminum alloy (duralumin), stainless steel half-hard beryllium copper and O-nickel (oxygen-free nickel) were studied. Two approximately 10 watt signals at frequencies near 3 GHz were used for excitation. Several rounded and pointed contact shapes with different joint pressures were investigated.

The strongest 3^{rd}-order and 5^{th}-order IM's were generated in the case of similar and dissimilar metal-metal contacts of mild steel, aluminum and stainless steel. The lowest products were generated with similar or dissimilar copper, brass, beryllium copper and nickel contacts. Dissimilar contacts of mild steel, aluminum and stainless steel with any of the other materials examined generated IM's which were either high or of intermediate value. Similar and dissimilar metal-metal contacts of electroplated gold, silver, rhodium, copper or tin did not exhibit strong IM products.

The largest 3^{rd}-order and 5^{th}-order IM product power levels were obtained for very low joint contact composition of the specimens used. It was observed that, for point contacts, the IM levels were more susceptible to a slight increase in contact pressure than in the case of slightly rounded and spherical contacts. Flexible coaxial cables with stranded inner conductors were found to give rise to strong 3^{rd}-order and 5^{th}-order IM products. A small amount of data showing the dependence of IM generation on total input power level for values between -24 and +8 dBW was presented. Various slopes of IM level vs input power level were obtained. Typically values of slope of 2.3 up to 3.5 for 3^{rd}-order products and 1.6 up to 6 for 5^{th} order products. Onset of nonlinearities was generally at very low levels (25-160 mW incident).

2. Metal-Insulator-Metal Junctions [B1-B22]: Intermodulation interference can be generated by the nonlinear semiconductor properties of unintentional diode junctions formed by metal-insulator-metal interfaces. Such junctions are frequently produced when oxidized metals are used to form metal-to-metal joints. A typical example is an Al-Aloxide-Al junction. Oxide layers 20-50Å thick give rise to nonlinear effects via an electron tunneling mechanism [B1]. Thicker oxide layers inhibit the tunneling effect resulting in linear junctions. Aging effects cause IM generation in Al-Aloxide-Al junctions to vary with time. Humidity also plays an important role both through effects on the thin oxide film and nonlinearities introduced by the properties of water as a polar dielectric. IM product levels reported in the literature are in the range 125 to 160 dB below local transmitter power level for UHF frequencies. Any

irregularity in the conductors can cause localized current concentration with subsequent increase in IM effects. Signal path components and surrounding structural parts may contain troublesome metal-insulator-metal junctions.

In operational systems metal-insulator-metal junctions exist in complex combination with other mechanisms such as pressure contact variation, tiny gaps, surface roughness and perhaps surface artifacts of various types. The junction nonlinear mechanism is difficult to study under such conditions. A highly idealized study of tunneling nonlinear effects for Al oxide films has been carried out [B1]. Laboratory formed junctions consisting of thin-film Al conducting strips separated by an oxidized insulating layer about 30Å thick were used. The Forlani-Minnaja [B5] equation expanded in a Taylor series to the fourth order in voltage [B5] is used to provide an analytical expression for the tunneling current J. There are uncertainties associated with this equation which are discussed in the referenced paper. The form given below was found to be an acceptable mathematical model.

$$J = \frac{me}{2\pi^2\hbar^3} \exp\left(-A\bar{\phi}^{1/2}\right)\left[\left(\frac{2\bar{\phi}^{1/2}}{A} + \frac{2}{A^2}\right)eV + \frac{A}{48\bar{\phi}^{1/2}}(eV)^3\right] \tag{4}$$

where

$$A = \frac{A\pi S\sqrt{2m}}{\hbar}$$

$$\phi(x) = \text{local barrier potential}$$

and the other parameters are shown in Figure 2.

The thin film Al-Al_2O_3-Al tunneling junctions were fabricated using standard evaporation and oxidation techniques. The procedure involves the vacuum evaporation of an aluminum strip of $\gtrsim$ 1500Å thickness onto a clean glass substrate. The strip is then allowed to oxidize at room temperature from 12 to 24 hours. Following this oxidation, a second similar strip is deposited at right angles to the first strip. The resulting junction sandwich area consists of two

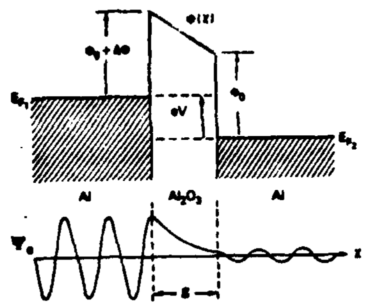

Figure 2.

Electron tunneling through the potential barrier of a thin insulating film between two conductors. The conductors of the sandwich structure are maintained at a potential difference of *V* such that there is a finite electron probability function ψ_e everywhere to the *right of the first interface. The resulting current is a nonlinear function of voltage.*

(After Bond [B1])

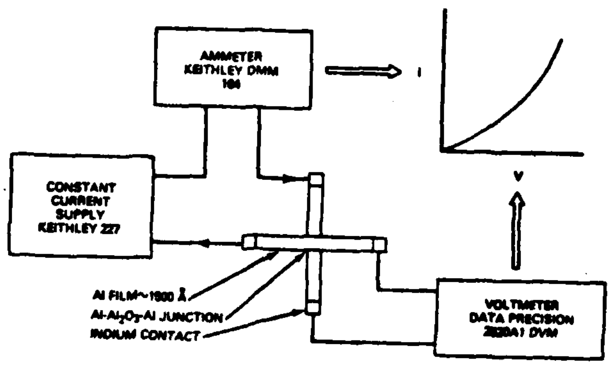

Figure 3.

Standard four-point arrangement for measuring the current-voltage characteristics of the *electron tunneling junctions.*

(After Bond [B1])

parallel plates of thin aluminum separated by an aluminum-oxide insulating film of about 30Å thickness.

The basic properties of these junctions important to IM product generation are the nonlinear resistive characteristics and the capacitance effects on RF conduction. The nonlinear dc current-voltage (I-V) characteristics of the junctions were measured with a standard four-point arrangement shown in Figure 3. A typical current-voltage curve (dc) is shown in Figure 4. On the scale shown, the experimental curve becomes visibly nonlinear at about 80 mV and exhibits a behavior typical of all the junctions measured. A computer program FORLAN was written to facilitate calculation of the tunneling current as a function of junction parameters. The program uses the complete analytical Forlani-Minnaja expression together with the near-linear (low-voltage) experimental values of I, V and G_o to determine the values of S for selected values of $\bar{\phi}$. The program can then generate full-range characteristic curves for these values of S and $\bar{\phi}$ to obtain the best fit to experimental V-I and R-V curves.

The I-V characteristics of all the junctions were discovered to be more reliably modeled by using an empirical cubic equation of the same form as Equation 4, but with different coefficients.

$$I = G_o V + \alpha G_o V^3 \tag{5}$$

Experimental values of G_o, I, and V at 100 mV and 200 mV, permit an average value of α to be obtained providing a satisfactory fit to the measured data. The solid line in Figure 4 shows an example of this procedure.

The junction parameters G_o α, $\bar{\phi}$, and S do not remain constant in time. Figure 5 shows the junction resistance for the device of Figure 4 as a function of applied voltage with time as a parameter. The curves show the sensitivity of the junction resistance to $\bar{\phi}$ and particularly to the insulator thickness S.

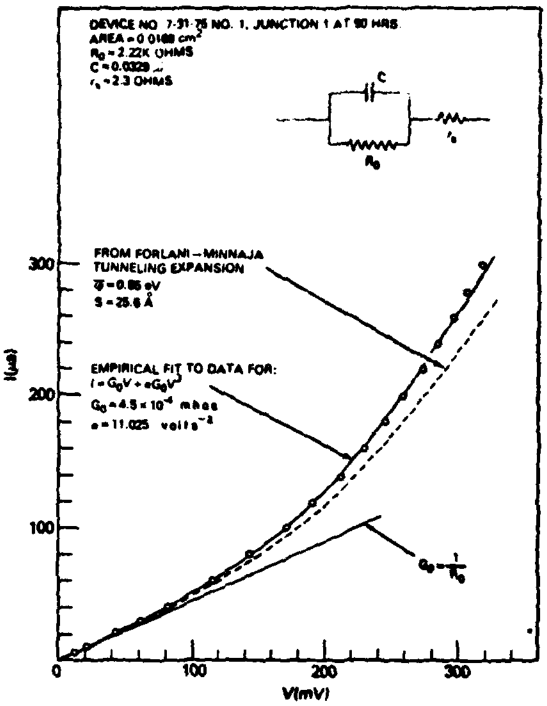

Figure 4.

The current-voltage characteristic curve for a 0.0168 cm^2 junction. On the scale shown, the experimental curve become visibly nonlinear at about 80 mV and exhibits a behavior typical of all of the junctions measured. The equivalent circuit of the junction is shown in the upper right.

(After Bond [B1])

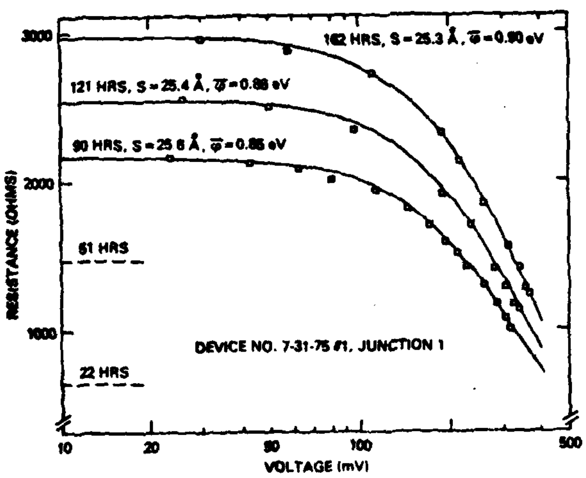

Figure 5.

The behavior of junction resistance as a function of voltage and time. The solid curves are generated by the FORLAN program and represent a best fit to the experimental points for the indicated values of $\bar{\varphi}$ and s.

(After Bond [B1])

The measurements carried out were specifically concerned with IM generation in the Fleet Satellite Communication System (FLTSATCOM) which has transmit and receive bands from about 240 MHz to 270 MHz and 290 MHz to 320 MHz, respectively. Considering two frequencies f_1 and f_2 in the transmit band at voltage levels V_1 and V_2, the input voltage V_{in} across a tunneling junction can be written as

$$V_{in} = V_1 \cos \omega_1 t + V_2 \cos \omega_2 t \tag{6}$$

The nonlinear output current for the junctions studied can be written as

$$I = G_o V_{in} + \alpha G_o V_{in}^3 \tag{7}$$

Retaining only the experimentally observed frequencies ω_1, ω_2, and $2\omega_2 - \omega_1$ in substituting Equation 6 into Equation 7 yields

$$\begin{aligned} I(t) &= G_o(V_1 \cos \omega_1 t + V_2 \cos \omega_2 t) + \frac{3}{4} \alpha G_o V_1 V_2^2 \cos(2\omega_2 - \omega_1)t \\ &= I_o(t) + I_{IM}(t) \end{aligned} \tag{8}$$

Frequencies of f_1 = 250 MHz and f_2 = 270 MHz were used as transmitter frequencies in all junction measurements.

A block diagram of the test facility is shown in Figure 6. Each transmitter power output can be varied independently from 0 to 100 W. The maximum third-order (290 MHz) IM generated by the test facility alone is $\lesssim$ - 140 dBm at 50 dBm (100 W) total power output from the diplexer. The tunneling junctions under test are placed between the diplexer output and 500 ft of RG-214 coaxial cable. The cable approximates an infinite transmission line and ideal termination. The power levels were adjusted so that $P_1 = P_2$ and the total power input P_I to the junction was usually set to 1.0 W. The total power input of any device was kept below ~4 W due to the limited ability of the thin film conductors to dissipate power.

IM measurements were made on several junctions. I-V characteristics for one such set of junctions are shown in Figure 7 with corresponding IM characteristics

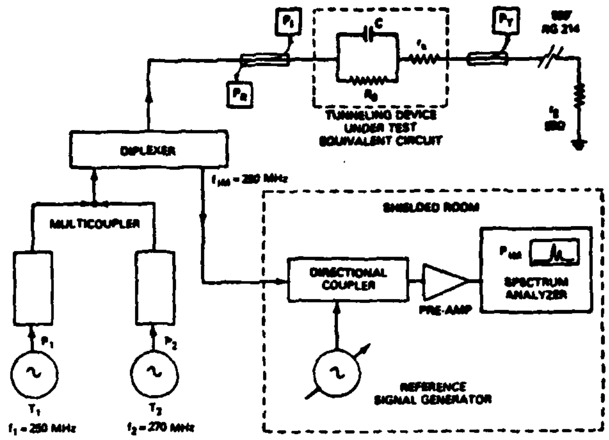

Figure 6.

Block diagram of the IM test facility operated by the NRL Special Communications Branch. The equivalent circuit of a tunneling junction is shown in the normal test location. Directional couplers and detectors are used to measure the incident, reflected, and transmitted RF power P_I, P_R, and P_T, respectively. The IM power P_{IM}, is measured at the spectrum analyzer by comparison to a calibrated reference signal generator.

(After Bond [B1])

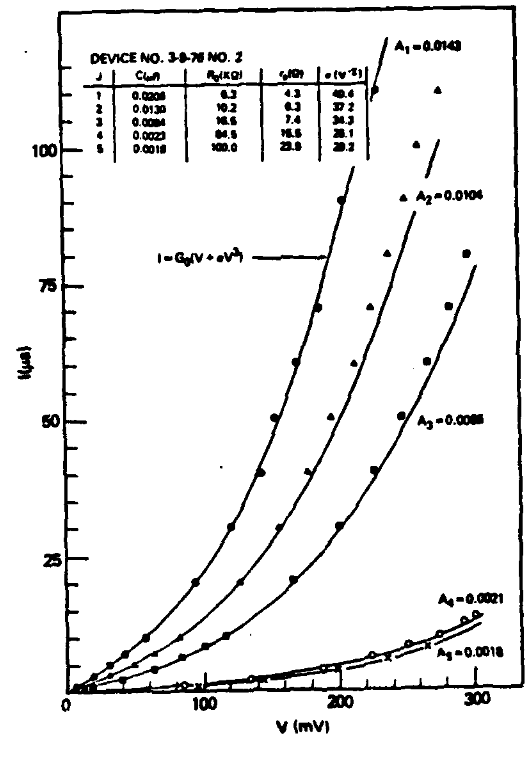

Figure 7.

Current-voltage characteristics as a function of area for five junctions. The corresponding junction parameters are shown in the upper left table.

(After Bond [B1])

in Figure 8. Ion implantation was attempted in hopes of eliminating or reducing IM effects.

Overall conclusions of the study of Al-Al_2O_3-Al junctions were as follows:

1. Tunneling junctions ranging in areas from ~ 0.015 cm^2 down to ~ 0.0015 cm^2 showed IM levels of about 150 dB to 110 dB below the transmitted power of 0.5 W. This corresponds to a P_{IM}/P_{signal} ratio of 10^{-15} to 10^{-11}, respectively. Since, a P_{IM}/P_{signal} ratio of $\lesssim 10^{-19}$ is generally desirable, the electron tunneling mechanism is seen to be a significant source of IM.

2. In Al-Al_2O_3-Al junction devices, time dependent behavior is prominent with the junction resistance increasing continuously for several hundred to several thousand hours followed usually by an abrupt self-shorting drop to fractions of an ohm. Such time-dependent behavior is assumed to take place independently in the numerous microscopic tunneling points in real hardware contacts. These mechanisms could contribute to the erratic fluctuation of IM observed in macroscopic contacts.

3. Ion implantation of $\gtrsim 10^{16}$ silver atoms/cm^2 in the oxide surface produced linear low-resistance and low-IM junctions but failed to stop the characteristic increase of junction resistance with time.

It should be recognized that this study was carried out using idealized junctions under laboratory conditions. Junctions in the "real world" would be more complex and would usually be accompanied by other nonlinearities in such fashion that the individual effects are very difficult to separate.

3. <u>Nonlinear Resistivity [A23-24]</u>: In addition to junction effects of various types, bulk conductors have a weak nonlinear characteristic that appears intrinsic to the material. In the past, IM sources in cables and connectors were almost universally attributed to current crossing a poor metallic contact

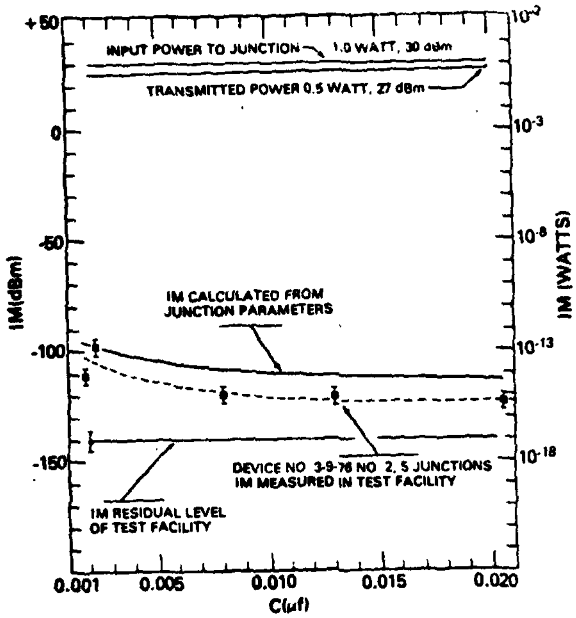

Figure 8.

Experimental and calculated IM power levels generated by electron tunneling as a function capacitance. The variation in capacitance results from a gradation in junction areas ranging from 0.0018 cm^2 to 0.0143 cm^2. All junctions were fabricated simultaneously and have the same oxide thickness of ~25 Å. The junction parameters and *I-V* characteristics for each of the five junctions are shown in Fig. 7.

(After Bond [B1])

in connectors and to poor braid contact in flexible cables. A recent study [A-24] has shown significant IM levels can arise from the intrinsic nonlinear properties of the conductors themselves. Passive nonlinearities of resistivity in conducting materials, in contrast with that due to contact junctions were studied by careful measurement and analysis. Forward and backward traveling wave IM's in a long transmission line were distinguished and interpreted. IM generation by steel, stainless steel, and graphite fibers were conclusively demonstrated.

Measurement Setup - A block diagram of the measurement setup used in this study of IM generation by nonlinear resistivity is shown in Figure 9. Two channel transmitting signals (f_1 = 245 MHz, f_2 = 268 MHz) originated from frequency synthesizers are amplified by separate power amplifiers to give an output of 44 dBm (25 watts) per channel. They are combined through a network of hybrids and filters in the transmit screen room and are then sent to the transmit port of the input test diplexer. The component under test (CUT) is connected between the two common ports of the two (input and output) test diplexers. The transmitted and reflected IM's are measured from the receive ports of the two diplexers with a spectrum analyzer. Using a low noise amplifier (NF = 2 dB) in front of the spectrum analyzer and with the IF bandwidth of the analyzer set to 10 Hz, the practical limit of a detectable signal is about -160 dBm.

The third order IM at frequency $2f_2 - f_1$ = 291 MHz, and the fifth order IM at frequency $3f_2 - 2f_1$ = 314 MHz were measured. The 7^{th} order IM cannot be measured readily due to the receive frequency band limitations of the test diplexers. It is generally agreed that power level in IM decreases as the IM order increases and that the third order IM is the strongest interference source. Only third order IM products were considered in the conducting material measurements that follow.

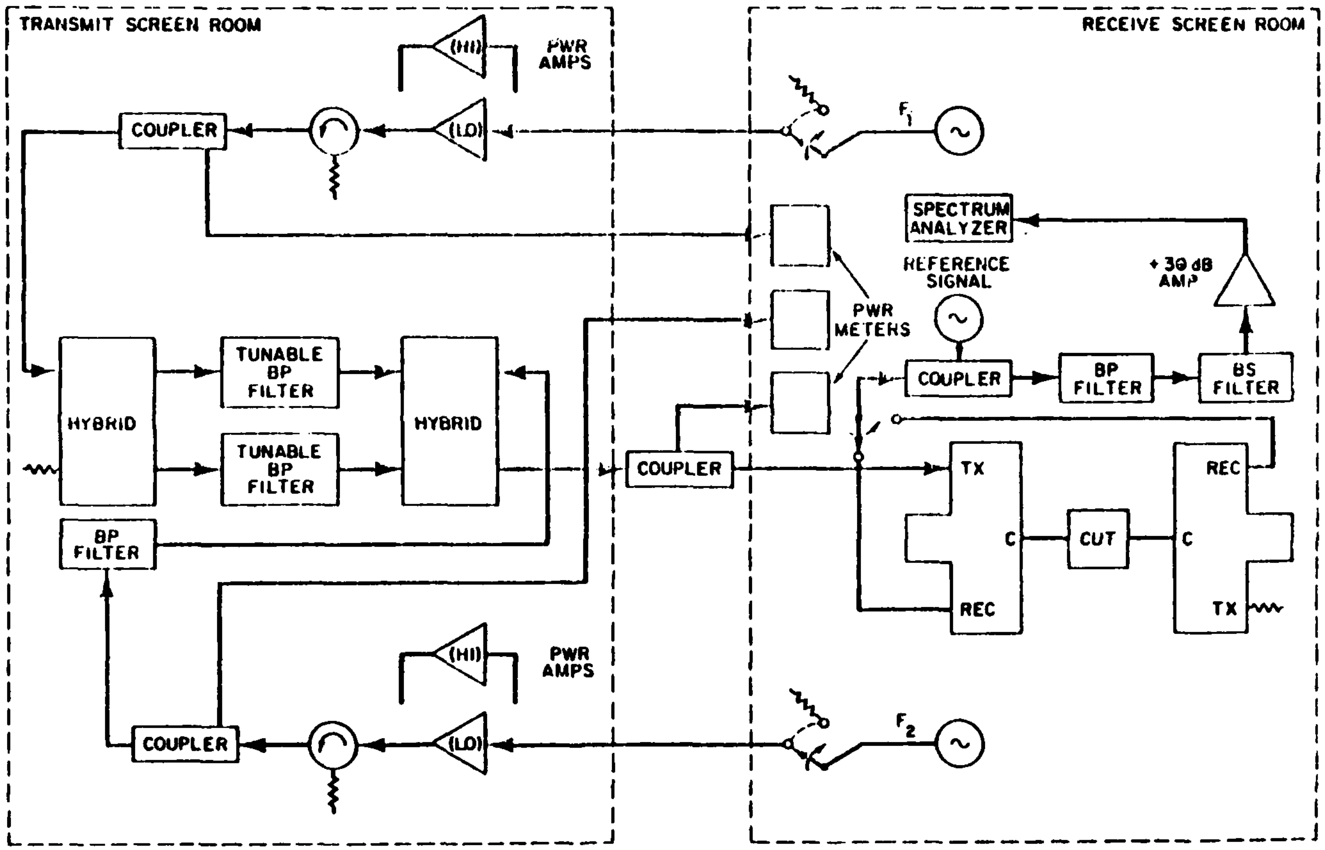

Figure 9. Block diagram of the IM measurement setup.
(After Lee [A23])

<u>Conducting Material Measurements</u> - To determine the IM levels due to different conducting materials, test samples made of various materials have to be put between the two test diplexers. To eliminate nonlinear contact impedance at the contact joints, a test fixture utilizing quarter wave coupling for the inner conductor of a large, rigid coaxial line was designed. Figure 10 is a sketch of the test fixture. The large, outer coaxial line with air dielectric has an outer conductor with ID = 0.563 inch and inner conductor with OD = 0.244 inch (characteristic impedance $Z_0 = 50\ \Omega$). The quarter wave coupling is accomplished by another coaxial line built inside the inner conductor. The test samples are made to form the inner conductor. For the inner coaxial line, the ID of the outer conductor is 0.200 inch and the OD of the inner conductor is 0.162 inch (characteristic impedance $Z_{0s} \approx 10\ \Omega$). The two conductors are separated by a commercially available Teflon tube of 0.024 inch wall thickness. The length of the inner conductor is chosen to be about two quarter wavelengths long at 250 MHz. The loaded Q of the resonant circuit is very low ($Q_L = Z_{0s}/8Z_0 = 0.04$); the return loss at the driving (transmit) frequencies is greater than 20 dB and at the IM_3 (receive) frequency of interest is better than 15 dB. Test samples of 0.162 inch diameter and 23.125 inch long with rounded ends were made of various conducting materials. Their pertinent electrical parameters are listed in Table I. The measured 3^{rd} order IM levels for input power levels of 25 watts (each source) together with the calculated current density in the test sample and minimum insertion loss at resonance are given in Table II. From Table II, the following preliminary conclusions can be drawn:

1. IM's generated in the forward and backward directions by standing waves have about the same level.

2. Good conductors such as copper, aluminum, and brass have apparent 3^{rd} IM levels about -120 dBm. The actual value may be lower, but the

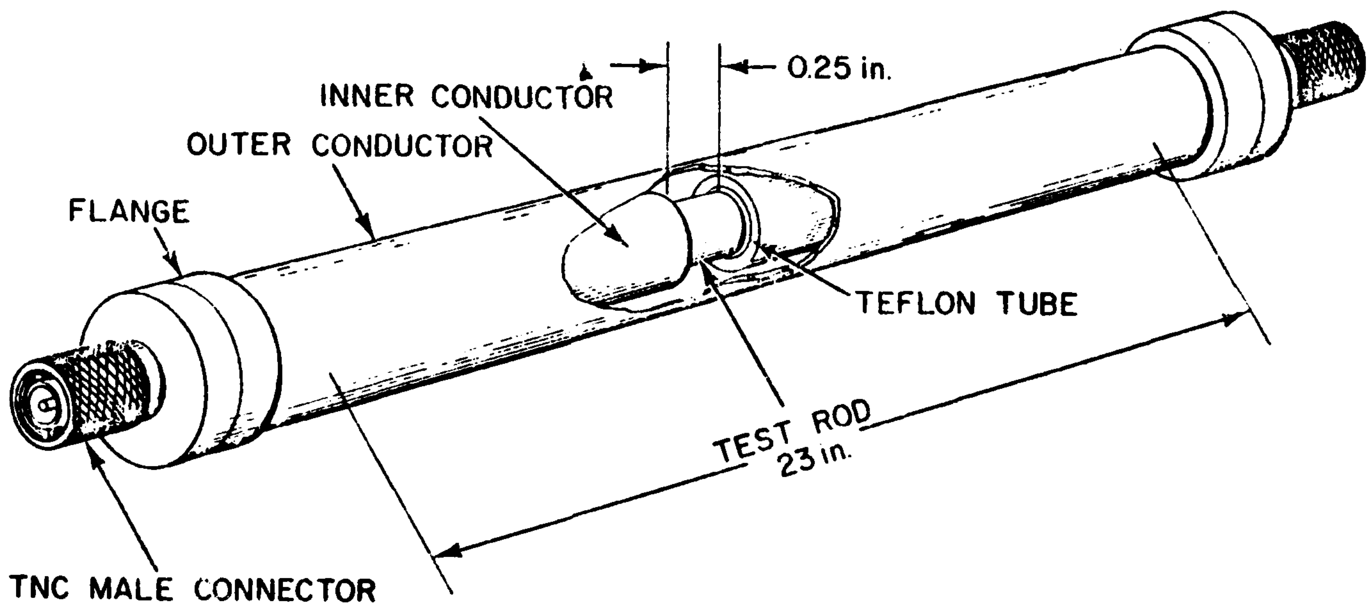

Figure 10. Cross-sectional view of the conducting material IM test fixture.

(After Lee [A23])

TABLE I

PERTINENT ELECTRICAL PARAMETERS OF TESTED CONDUCTORS
(After Lee [A-23])

Conductor	Conductivity at Room Temp. $\sigma \times 10^{-7}$ mohs/m	Relative Conductivity σ_r	Relative Permeability μ_r	Skin Depth at 250 MHz $\delta \times 10^4$ inches
Copper	5.8	1	1	1.64
Aluminum	3.7	0.63	1	2.07
Brass	2.3	0.4	1	2.59
Stainless Steel*	1.4	0.24	1.02 (annealed)	3.31
Graphite**	0.01	0.0017	1	39.5
Cold-Rolled Steel	1.0	0.17	180	0.30

*Type 303

**The graphite rod was "pultruded" (pulled from the processing equipment), and supplied by Columbia Products Co., Columbia, S.C. Hercules graphite fiber-AS with anhydride epoxy resin was used. All fiber orientation was unidirectional.

TABLE II

MEASURED IM LEVEL AND INSERTION LOSS
(Two Sources-25 watts Each)
(After Lee [A-23])

Material	Forward IM_3 dBm	Backward IM_3 dBm	Calculated Current Density A/cm^2	Minimum Insertion Loss dB
Copper	-120	-118	1,857	0.05
Aluminum	-124	-121	1,471	0.05
Brass	-120	-122	1,176	0.08
Stainless Steel	-105	-102	920	0.1
Graphite	-61	-60	77	0.4
Cold-Rolled Steel	-44	-44	10,152	0.3

minimum measurable level may be limited by the TNC connectors between the test diplexers and the IM test fixture.

3. Stainless steel generates IM's higher than good conductors such as copper, brass or aluminum but lower than graphite and cold-rolled steel.

4. Graphite generates very high level of IM's due to nonlinear resistivity.

5. Cold-rolled steel generates the highest IM level probably due to its nonlinear permeability.

4. Nonlinear Permeability [A22, A21]: The nonlinear B/H characteristics of ferromagnetic materials is very bad from the IM point of view and gives rise to severe intermodulation interference. Coaxial connectors and adapters containing ferromagnetic materials produce 30-50 dB more IM interference than nonmagnetic counterparts. Stainless steel type 303 (Magnetic alloy), Kovar-glass hermetic seals, and nickel plated connectors have very bad IM performance. Type 303 stainless connectors using two signals of only -45 dBm each was reported to generate IM product levels greater than -90 dBm [A21]. IM product levels generated by KOVAR were greater than those generated by stainless steel, which in turn were greater than those generated by nickel plating. Gold plating of stainless steel connectors reduced the IM levels but still did not provide the very low levels obtained from ordinary silver plated brass devices.

Another source of IM interference caused by nonlinear B/H characteristics is tiny magnetic artifacts introduced inadvertently during manufacture. Typically, the magnetic particles are very small and are due to the use of iron or nickel tools in forming the part, or from particles deposited from dust in the air. Problems have been noted with semirigid coaxial cable formed using steel dies.

IM levels generated by ferromagnetic materials can be very high, in some instances only 20 to 30 dB below the local power level. A new type hermetic seal has been developed with no ferromagnetic parts due to problems encountered with Kovar-glass seals during development of the MARISAT and related communication systems.

V. CONNECTORS AND CABLES

IM generation in connectors and cables has been investigated by several workers [C1-C9, A-21, A-23] including two recent studies [A-21, A-23].

Connectors - A variety of connector types have been investigated. Use of materials such as type 303 stainless steel or Kovar (in hermetic seals) has been shown to produce very high IM levels. Lee [A-23] measured various commerically available TNC adapters of different sex combinations. The results showed consistently that the surface material used in the connector is an important factor affecting IM levels. It seems contact, conductivity and magnetic properties of the surface material are all important. Typical measured IM levels are summarized in Table III.

TABLE III

MEASURED IM LEVELS OF TNC ADAPTORS
(Two Sources-25 watts Each)
(After Lee [A-23])

Body Material	Surface Material	Reflected 3rd Order IM Level in dBm
Brass	Silver Plated	-120 to -125
Aluminum	Electroless Nickel Plated	-117 to -130
Brass	TR-5* Finish	-90 to -111
Stainless Steel	Stainless Steel	-88 to -105

*TR-5 is a trade name of Kings Electronics Co., Inc. for a surface finish.

From Table III notice that connectors with stainless steel surface finish generated highest level IM's which confirms other measurement results [C-9]. Stainless steels are ordinarily considered to be "nonmagnetic." However, it is in fact magnetic. Under annealed conditions their permeability is listed to be 1.02. Under stress this value could be much higher.

The next highest IM contributer is TR-5. This finish appears to involve layers of plating on brass, including copper, zinc and nickel, a total of less than 1 mil in thickness. At the frequency range used, the skin depth for good conducting material is in the 0.2-0.3 mil range; thus all three layers may have influence on the overall IM level. It is not clear how much IM is contributed by the hard copper-zinc layer through poor contact and how much by the nickel layer through non-linear magnetic property.

In electroless nickel plating, nickel-phosphorus alloys are formed. These alloys have a higher electrical resistance than that of nickel. If the deposits contain phosphorus in excess of 8 percent, the alloy is then "nonmagnetic." This property of electroless nickel plating may be the reason for lower IM levels for the electroless nickel as compared to the TR-5.

Similar tests of type N connectors yielded similar results. Gold plated connectors usually work as well as silver plated ones. Due to their larger size, type N connectors are expected to have lower IM than TNC types. However, since the TNC connectors in the test diplexers always form part of the component under test (CUT), this conviction cannot be demonstrated. However, for low IM components we always use silver or gold plated connectors. Limited tests on GR-900 gold plated connectors showed an IM level of -120 dBm with two input signals of 25 watts each.

Reports on the other connectors and adapters are available in reference [A-21].

Cables - A variety of cables have been tested for IM generation including braided flexible cables and semirigid solid conductor types [A-21, A-23]. Lee [A-23] tested a substantial number of cables with different connectors. For most cables the measured IM levels were dominated by the connector contributors. One important IM source was found at the cable outer conductor contact with the connector body. Mechanical support in this area must be good to avoid problems.

IM level is very sensitive to vibration or movement in this critical area. Some typical IM ranges are given in Table IV.

From the table, with two input signals of 25 watts each, RG-214/U or 0.141 inch semirigid lines can be seen to attain low reflected IM (below -120 dBm) by careful selection of connectors and following good cabling procedure. Measured IM levels were also found to depend on cable length. Lee derived a relationship showing this dependence. The result for third order IM is shown in Figure 11.

In previous studies, cables similar to RG-214/u in size were measured [C-2]. Length of the cables chosen were 0.5 m (1.6 feet), 1 m (3.3 feet) and 5 m (8.2 feet). The highest cable insertion loss tested in these studies is estimated to be 0.4 to 0.5 dB for the 5 m cable. Thus, the cables tested were all well below the condition for maximum IM level (about 5 dB loss). It was observed that the longer the length of the cable, the higher the level of the IM's. Thus, measured results generally support the theoretical analysis.

TABLE IV

MEASURED IM LEVELS OF COAXIAL CABLES
(Two Sources-25 watts Each)
(After Lee [A-23])

Cable Description	Connector	Center Pin	Outer Conductor	Reflected 3rd Order IM Level (dBm)
RG 214/u	TNC	Gold plated	Gold Plated	-90 to -122
	N	Gold plated	Nickel plated	-95 to -100
	N	Silver Plated	Silver plated	-120 to -127
	N	Copper plated	Copper Plated	-132 to -138
0.141" semi rigid	SMA solder	Gold plated	Gold plated	-105 to -110
	SMA crimp	Gold plated	Gold plated	-108
	TNC	Silver plated	Silver plated	-123 to -132
RG 58/u	TNC	Gold plated	Nickel plated	-66 to -113

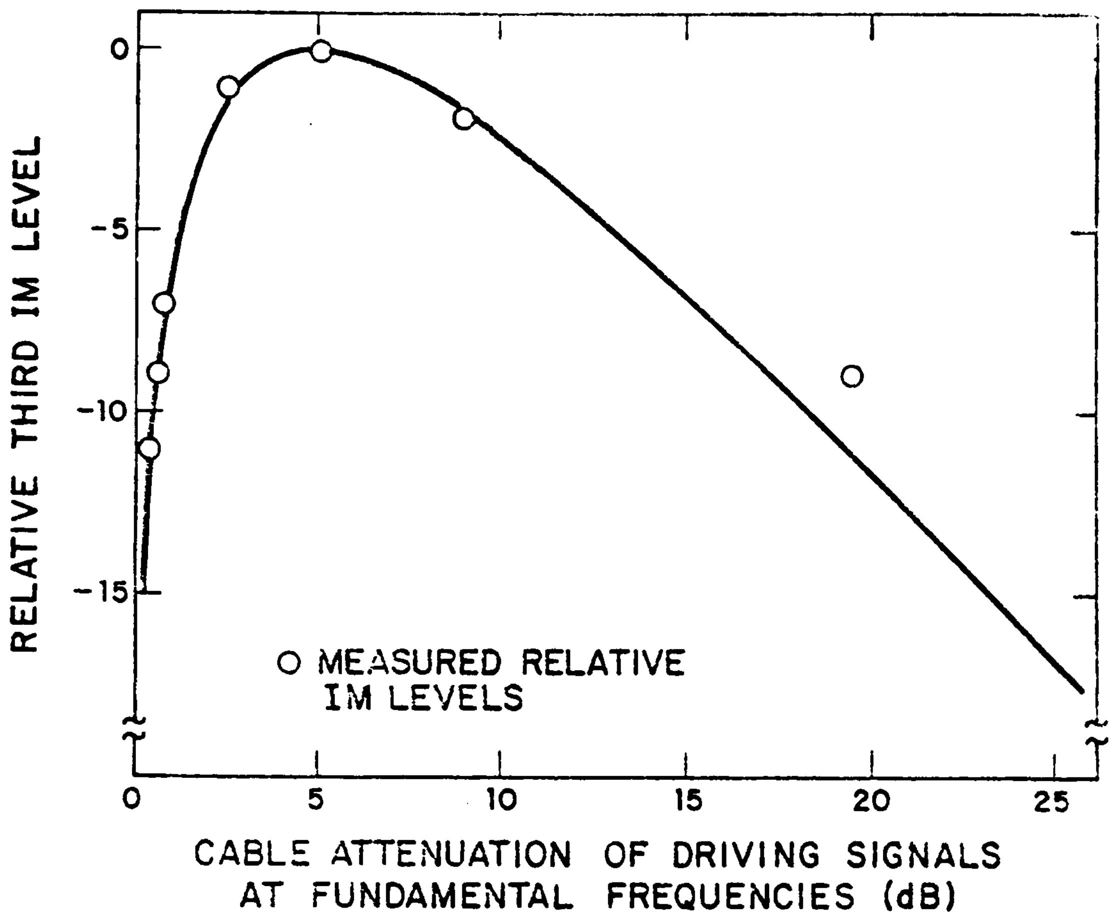

Figure 11. Relative variations of the forward 3rd order IM level with cable length in terms of cable loss.

(After Lee [A23])

VI. POTENTIALLY TROUBLESOME PROCESSES AND MATERIALS

Several manufacturing processes and some types of materials have been identified as particularly likely to cause passive IM generation problems. Avoidance of these processes and materials where possible and special care otherwise is recommended.

Processes

- Grinding and polishing
- Plating (particularly electroless nickel)
- Painting (aluminum and other metal particle paints)
- Bonding (pressure joints, adhesives, soldering, brazing, welding)
- Surface artifacts (particularly magnetic)
- Any process producing sharp points

Materials

- All ferromagnetic metals (iron, nickel, Kovar, etc.)
- Boron nitride, duroid, Al-Kapton, microwave absorbers, graphite, Q-clad, Al-Mylar, carbon metalized films, conductive glass, ferrites
- Anodized aluminum
- Metal particle paints
- Metal bonded epoxies
- Metal chips, solder, and conductive epoxies
- Polar dielectrics

In general any process that can leave a surface rough, scratched, nicked, pitted, or with imbedded magnetic or other surface artifacts is potentially troublesome with respect to IM generation. Oxide layers formed in plating, plating with magnetic materials, peeling or leafing aluminum or other metal particle paints, oxidation from solder flux, and similar things are likely sources of difficulty. Materials with nonlinear permeability, conductivity, or permittivity are to be avoided if possible.

VII. CONCLUSION AND IM REDUCTION COMMENTS

IM interference generated by supposedly "linear" passive system components has created problems in several satellite systems, including FLTSATCOM, MARISAT, and Lincoln Experimental Satellites 5 and 6. These unwanted, weak nonlinearities are difficult to track down and characterize quantitatively. Limitations and operational problems imposed by passive IM generation are sure to become increasingly severe as higher power transmitters and more sensitive receivers for multi-channel communications systems are developed.

Each time passive IM interference has occurred, extensive efforts were made to fix the problem. Usually IM levels were brought to a tolerable level by a combination of cleaning the sensitive parts, tightening joints, polishing surfaces, avoiding ferromagnetic materials, etc. In certain pressing situations, the remedy was to replace the traditional single antenna/diplexer system with separate transmit and receive antennas. The isolation between the two antennas significantly alleviated the stringent IM requirements at the receiver input port. However, two separated antennas is a disadvantage from weight, deployment and cost viewpoints.

From the experiences recorded in the references, the following items have been proven, or suspected, of dominating the nonlinearity contribution in passive "linear" systems.

Connections

- Waveguide flanges and coaxial connectors
- Metal-Metal pressure contacts, screw-down covers, spring-finger contacts, press-fit contacts, point contact, tuning screws
- Corrosion caused by solder flux

Surface finishes and materials

- Sharp rough surfaces, burrs, cracks, scratches
- Imbedded chips, filings, filament conductors
- Water vapor, solder flux contamination
- Magnetic materials (steel, nickel, Kovar, ferrite, etc.)

Physically, except for magnetic materials, it appears that all the other items can be traced back to three general causes.

- Unintentional diode junction effect
- Plasma effect (local high field causing corona)
- Local high current density causing resistive nonlinearity

Nonlinearity suppression requires precision manufacturing, tight assembly control, and extreme care to ensure tight, clean joints and smooth, clean surfaces. Designs should be such as to minimize current density and high voltage gradients.

In general, the level of passive IM interference can be reduced in several ways.

1. Reduce the degree of the nonlinearity causing the IM generation by proper choice of materials and construction techniques.

2. Reduce the effects of the nonlinearity by reducing the incident field strengths. The input power levels are usually fixed by other constraints, therefore,

   a. reduce power level at the nonlinearity by using more paths in parallel

   b. use physically larger transmission lines to reduce local field strengths

   c. arrange system so that strong fields at frequency 1 and frequency 2 do not occur at the same place

d. when both signals must coexist, use low Q circuitry so that the field strength or current density is not adversely enhanced.

From the literature examined, it is apparently relatively common to require IM levels below -140 dBm with local transmitter power levels of 100 watts or more. Receiver sensitivities of about -90 dBm, -110 dBm, and -140 dBm are reported in the references.

Results of this literature search and of contacts with various industry and government organizations show that passively generated IM interference is a very real and increasingly important problem. Passive IM generation reported arises from sources as diverse as Al-oxide-Al interfaces in riveted Al panels/to coiled rusty chain on a ship/to microscopic magnetic particles imbedded in the walls of coaxial cables. The topic is complex. In an operational situation several of the nonlinear mechanisms may be (and usually are) present simultaneously. Experimental investigations of the specific nonlinear mechanisms have of necessity been highly idealized relative to operational conditions.

From the literature, ferromagnetic materials are the worst offenders in generating IM interference with reported IM levels as large as only 20-30 dB below local transmitter levels. Next are metal-metal joints [with results that are highly dependent on applied pressure] having reported values of only 40-100 dB below local transmitter levels. Reported IM levels for electron tunneling in metal-insulator-metal junctions are in the range of 125-160 dB below local transmitter levels.

A number of shortcomings are apparent from the literature search. First, there is very little data on variation in IM generation for any of the nonlinear mechanisms as functions of incident power level or transmitted frequencies. Most of the reported studies are at specific fixed frequencies and power levels. The second difficulty is that there is seldom sufficient information on the measurement procedures and setups to enable reasonable comparisons to be made from experiment-to-experiment or paper-to-paper.

Passive IM generation is clearly a problem of considerable significance. Limited progress has been made in understanding the basic mechanisms involved, but much remains unknown. Some IM reduction techniques have been devised and proven effective, particularly with regard to magnetic materials on shipboard. Additional programs are clearly needed to fill in the many information gaps.

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